The Science of Titan and its Future Exploration

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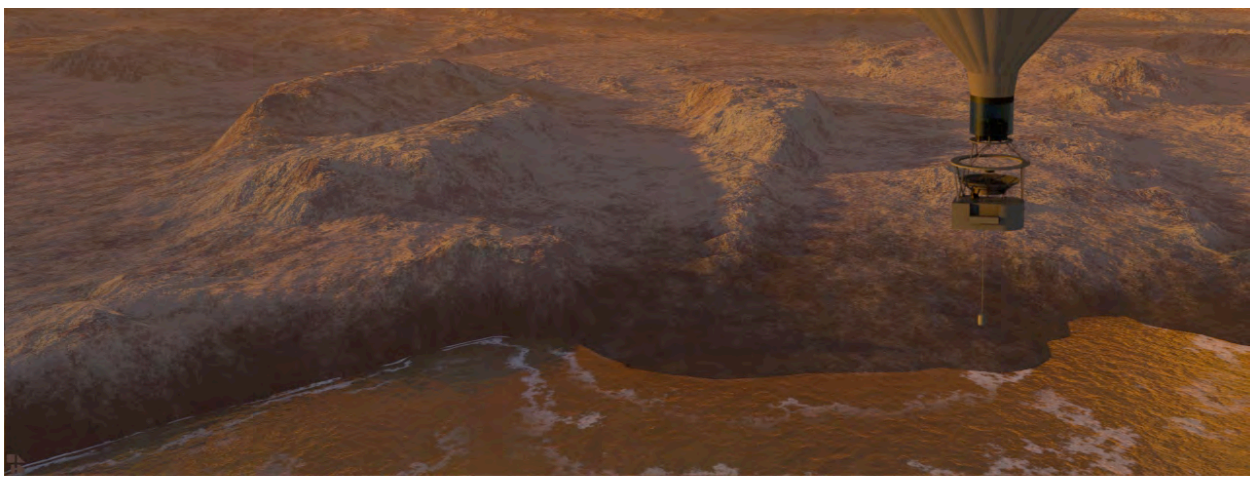

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1. **The Relevance and Prominence of Titan Exploration**

Saturn's largest moon Titan has been an enigma at every stage of its exploration. For three decades after the hazy atmosphere was discovered from the ground in the 1940s, debate ensued over whether it was a thin layer of methane or a dense shield of methane and nitrogen. Voyager 1 settled the matter in favor of the latter in 1980, but the details of the atmosphere it determined raised an even more intriguing question about the nature of the hidden surface, and the sources of resupply of methane to the atmosphere. The simplest possibility, that an ocean of methane and its major photochemical product ethane might cover the globe, was cast in doubt by Earth-based radar studies then eliminated by Hubble Space Telescope and adaptive optics imaging in the near-infrared from large ground-based telescopes in the 1990s. These data, however, did not reveal the complexity of the surface that Cassini-Huygens would uncover beginning in 2004. A hydrological cycle appears to exist in which methane (in concert with ethane in some processes) plays the role on Titan that water plays on Earth. Channels likely carved by liquid methane and/or ethane, lakes and seas of these materials—some rivaling or exceeding North America's Great Lakes in size—vast equatorial dune fields of complex organics made high in the atmosphere and shaped by wind, and intriguing hints of volcanic flows of water across an ice crust suggest a world with a balance of geological and atmospheric processes that are similar to those operating on Earth. Deep underneath Titan's dense atmosphere and active, diverse surface are tantalizing hints of a liquid water, or water-ammonia, ocean. Exploration of this varied and active world beyond Cassini's equinox and solstice investigations of seasonal change will require landed studies, airborne sounding platforms (most plausibly from a balloon), and an orbiter.

2. Titan as an Organic-Rich Environment

The Cassini-Huygens era of investigation has furthered our understanding of Titan as the largest abiotic organic factory in the solar system. The abundance of methane and its organic products in the atmosphere, seas and dunes exceeds by more than an order of magnitude the carbon inventory in the Earth's ocean, biosphere and fossil fuel reservoirs. The extent to which present-day Titan resembles the prebiotic Earth is not clear, since the oxidation state of the early Earth is not well determined. Certainly the present Titan is more oxygen-poor than was Earth, but formation of organic haze may nonetheless have taken place on our own planet early in its history. Organic haze formation under UV illumination takes place as long as the carbon to oxygen ratio is above about 0.6, and methane photolysis on the early Earth would have provided a richer organic feedstock than the delivery of organics from meteorites. In addition to the prebiotic synthesis role, haze on the early Earth may have been significant in the radiative balance (acting as an anti-greenhouse agent) and in particular in providing UV opacity which may have protected nascent biota in the absence of an ozone shield. Thus, while the analogy of Titan to the early Earth is not perfect, it is potentially quite close. Titan-like planets may be common in the universe—indeed planets around the most common stellar type, the cool M dwarfs, at the distance of the Earth from the Sun will be as cold as Titan. Titan may usefully inform us about their organic chemistry and potential habitability.

The surface of Titan appears at first glance to be an unlikely location for extant life, at least terrestrial-type life. There are photochemically derived sources of free energy on Titan's surface that could support life, which would have to be an exotic type of life using liquid hydrocarbons as solvents (Committee on the Origin and Evolution of Life 2007). Terrestrial bacteria can in fact derive their energy and carbon needs by 'eating' tholins. In this sense, a methane-rich atmosphere may act as a 'poor-planet's photosynthesis', providing a means to capture the free energy from ultraviolet light and make it available for metabolic reactions. Benner et al. (2005) have speculated that a form of life, or at a minimum a kind of organized chemical system, can be sustained in liquid hydrocarbons known to be stable on Titan's surface; the National Academy of Sciences report "The Limits of Organic Life in Planetary Systems" (2007) emphasized the importance the discovery of such a system would imply.

3. Titan as a Model for Planetary Climates with Rapid Loss of Volatiles

Far from the Sun, methane plays the active role on Titan that water plays on Earth, acting as a condensable greenhouse gas, forming clouds and rain, and pooling on the surface as lakes. Titan's icy surface is shaped by impact craters, tectonics, fluvial and lacustrine erosive processes involving liquid methane and possibly ethane, and by tidally driven winds that shape drifts of aromatic organics into long linear dunes. Volcanism involving water and melting point depressants like ammonia has been suggested but no definitive evidence exists.

The analogies with the Earth are intriguing. Most obvious is the existence of a hydrological cycle involving methane clouds, rain and at least transient rivers. While the possibility of such a cycle had been noted as soon as the proximity of Titan's surface conditions to the methane triple point had been noted in Voyager data, the first evidence of clouds emerged in spectroscopic data and in Hubble Space Telescope (HST) images Subsequent observations showed clouds to be evolving on timescales of only hours, suggesting that precipitation may be occurring, and several years prior to Cassini, large ground-based telescopes with adaptive optics systems showed massive variable cloud systems around the south pole (where it was approaching midsummer). Cassini observations soon after its arrival in 2004 showed much detail on these clouds, and showed that the cloud tops ascended at velocities of order a meter per second, comparable with those predicted in models. These clouds, then, seem fully consistent with cumulus convection like those seen on Earth in desert summer.

Titan presents an interesting variation on the Earth's hydrological cycle. While the overall intensity of the cycle is weak, the available solar heating to evaporate surface moisture and drive the cycle is tiny, and not substantially compensated by the lower latent heat of methane compared with water. Thus, instead of the ~100 cm of annual rainfall observed on Earth, Titan must see on average only about 1 cm per (Earth) year. However, Titan's thick atmosphere can hold a prodigious amount of moisture, equivalent to several meters of liquid. Thus, where Titan dumps the moisture out of its atmosphere (which to a crude approximation, is what happens in violent rainstorms, as indicated in models of Titan rainclouds, it would require ~1000 years to recharge the atmosphere. The corresponding numbers are ~10 cm and a month for the present-day Earth. A warmer atmosphere can hold more moisture, and may thus see more intense storms separated by longer droughts, a pattern being discerned in the present epoch of global warming. Titan thus has a greenhouse hydrology taken to extremes.

Titan's clouds are not limited to convective cumulus. A pervasive, lingering cloud of ethane particles has been observed over the northern polar regions in the present season (northern late winter), probably related to the down-welling of organic-rich air over the winter pole. Additionally, sporadic small cloud streaks have been noted at mid-latitudes with a possibly non-uniform longitude distribution. There is presently debate as to whether these might be associated with the Hadley circulation and/or tides, or whether they are tied to surface features, either as orographic clouds, or clouds triggered by surface venting of methane. Some support for a low-latitude methane supply has been noted in models (much as the Martian climate causes water to migrate to high latitudes) that point out that the low latitudes on Titan should progressively become desiccated in methane, unless replenished by a surface source.

4. Titan's Geology

Fluvial modification of the surface was very evident at the Huygens landing site (Figure 1). Not only were steeply incised channels a few kilometers long and ~30 m across observed in the bright highland (which models of sediment transport suggest can be formed in methane rainstorms), but the knee-height vista from the probe after landing showed rounded cobbles characteristic of tumbling in a low-viscosity fluid. Radar imagery has revealed channels on much larger scales than those seen by Huygens.

Radar-bright channels (probably cobbled streambeds) have been observed at low and mid-latitudes, while channels incised to depths of several hundred meters are seen elsewhere, and at high latitudes radar-dark, meandering channels are seen that suggest a lower-energy environment where deposition of fine-grained sediment occurs. Whether these larger channels—some of which exceed a kilometer in breadth—and the large-scale flow features near the landing site

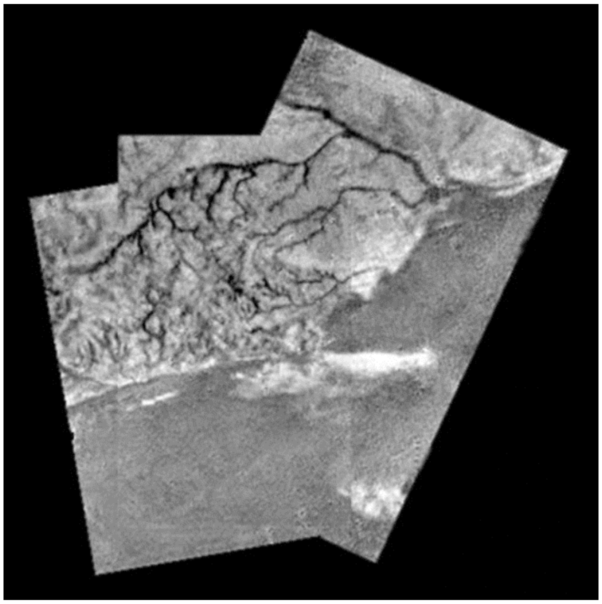


Figure 1. *Fluvial features at the Huygens landing site imaged by the DISR camera. The thickest channels are ~10 m across.*

would require a different climate regime to be formed remains to be determined—the flow of methane rivers in an unsaturated atmosphere

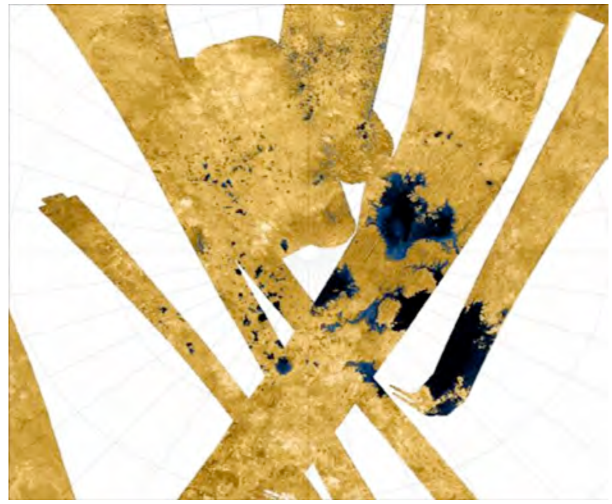


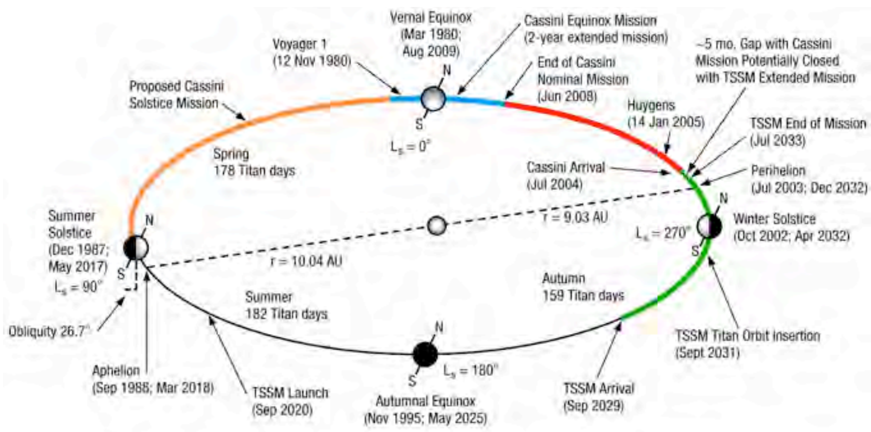
Figure 2. *Mosaic of the northern hemisphere lakes (dark areas). (NASA/JPL, USGS)*

on Titan is very analogous to the problem of ephemeral water flow on Mars—finding out whether the rivers dry out, freeze solid, or drain into an ephemeral sea will depend on presently unknown topographic and meteorological factors.

Beginning in July 2006, a series of flybys of the high northern latitudes of Titan began in which the Cassini orbiter RADAR imaged a variety of very dark features that have been interpreted to be liquid-filled basins—“lakes” (Stofan et al. 2007). The features range in size from less than 10 km^2 to at least 100,000 km^2. They are confined to the region poleward of 55°N. To date some 655 such features have been identified and mapped over seven Titan flybys (Figure 2).

Mapping indicates that above 65°N the dark lakes occupy 15% of the terrain imaged so far. Bright lakes—features that appear similar to the radar-dark lakes but have little or no brightness contrast with their surrounds—tend to replace the dark lakes equatorward of 70°N. An intermediate class of lakes that are somewhat darker than their surroundings, but often show faint features within them, has a latitudinal distribution similar to that of the bright lakes. Neither is seen above 77°N, where the dark lakes predominate. Size selection does not appear to be present in the dark lakes; both very large and very small examples exist. (Coverage by Cassini RADAR in the southern high latitudes is very poor; lower resolution imaging and VIMS data show just one large lake over 200 km long).

The hypothesis that the dark lakes are filled with liquid is advanced based on several arguments. First, the dark lakes are in many—but not all places—extremely dark, with reflectivity values below the noise level of the radar system. Since Cassini RADAR never operates in imaging mode at 0^o—nadir—incidence, the lack of return indicates reflection off a surface smooth on the scales of the 2.16 cm wavelength of the radar system. A calm liquid surface would produce the result. Few natural solid surfaces can appear so dark. The Huygens landing site was littered with 1–10 cm-scale pebbles and appeared bright to the radar system; features as dark as the lakes do not appear at equatorial or mid-latitudes (Figure 3.). Evidently, then, the physical surface causing the coherent reflection away from the radar antenna is typical only of the high latitudes and not simply of plains areas devoid of pebbles.



Orbital motion of Titan and Saturn around the Sun during one Saturn year. L_s denotes the Kronocentric (Saturnicentric) orbital longitude of the Sun that characterizes the season.

Figure 4: Seasonal phases of missions to Titan, including Voyager 1, Cassini (nominal, equinox and solstice missions) and TSSM assuming a 2020 launch. Seasons refer to the north. From the TSSM report.

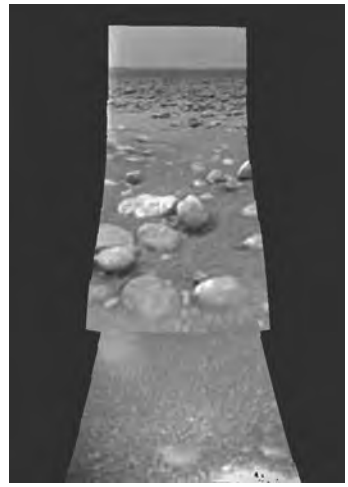


Figure 3. *Pebbles 10–15 cm in size litter the scene in front of the landed Huygens probe. Made of ice and possibly coated with organics, their rounded form suggests they were once tumbled by liquids. Image at the bottom is out of focus because of proximity to the camera. ESA/NASA/JPL/U. Arizona.*

Second, radiometry measuring the natural thermal emission at the 2.16 cm wavelength of the Cassini RADAR indicates that the dark lakes emit more thermal energy than the surroundings—consistent with hydrocarbons and inconsistent with a smooth surface of water-ice or ammonia-ice, assuming the exposed surrounding crustal material is water-ice. Third, the morphology of the boundaries between the largest of the dark lakes and the surroundings resembles a terrain flooded by liquid, with the dark material appearing to flood valleys between hilly terrain and in some cases occupying networks of channels that feed into or out of the lakes Finally, the latitudinal restriction on the occurrence of the dark lakes is consistent with global circulation models that predict precipitation of methane onto both or at least the winter pole, together with the decrease in surface temperature poleward . Currently the northern pole is approaching spring equinox in an annual cycle that is 29.5 years in length.

Assuming that the darkest of the northern hemisphere lakes are filled with liquid, it is of interest to know their depths both to understand the total amount of liquid they contain and to understand the underlying geology that has formed them. Both methane and ethane are relatively transparent at 2 cm wavelength, with recent laboratory measurements suggesting absorption lengths (1/e diminution of the signal) of order meters. The darkest lakes—which return no radar signal above the instrument noise floor—may therefore have depths that exceed orders of 10 m. The lakes that show faint features such as channels may be less than ~10 meters deep allowing the bottom to be seen. The presence of channels suggests these lakes periodically empty and are then subjected to channel formation through flow of methane from the surroundings.

ISS has documented dozens of such features near the South Pole, and the radar has begun to reimage these. In the intervening 4 years, *changes in the distribution of south-polar surface liquids have occurred, and some changes occurred in the space of one year. Repeated observations of the polar regions will be important for understanding the methane cycle as well as assessing the total methane inventory.* Observing the southern hemisphere at close range during southern springtime will permit assessment of whether more lakes are present there then. This will require a mission timed to arrive in a seasonal sense prior to the time of arrival of Cassini-Huygens; Cassini itself will not last until the next southern spring (Figure 4).

5. Questions Remaining for a Future Mission

Cassini-Huygens will leave us with many questions that will require a future mission to answer. These include whether methane is outgassing from the interior or ice crust today, whether the lakes are fed primarily by rain or underground methane-ethane aquifers (more properly, “alkanofers”), how often heavy methane rains come to the equatorial region, whether Titan’s surface supported vaster seas of methane in the past, and whether complex self-organizing chemical systems have come and gone in the water volcanism, or even exist in exotic form today in the high latitude lakes. The composition of the surface and the geographic distribution of various organic constituents remain poorly known. Key questions remain about the ages of the surface features, specifically whether cryovolcanism and tectonism are actively ongoing or are relics of a more active past. Ammonia, circumstantially suggested to be present by a variety of different kinds of Cassini-Huygens data, has not been seen. The presence of a magnetic field has yet to be established. The chemistry that drives complex ion formation in the upper atmosphere was unforeseen and is poorly understood. A large altitude range in the atmosphere, from 400–900 km in altitude, remains poorly explored after Cassini. Much remains to be understood about seasonal changes of the atmosphere at all levels, and the long-term escape of constituents to space.

Cassini’s brief flybys provide only piecemeal estimates of the atmospheric loss rates of methane and its products from photochemistry and energetic particle chemistry. The nature of Titan’s ionosphere in terms of its three-dimensional structure is not known and not achievable with Cassini. How does the ionosphere form and what is the variation in exchange of species and energy with the Saturn magnetosphere? What happens to the ionosphere as Titan passes in and out of the solar wind?

Cassini data hint at direct escape of methane being competitive with loss by photochemistry. This is paradigm changing, but is based on indirect derivation of vertical mixing in the upper atmosphere from the profile of radiogenic argon above 900 km. What is the vertical profile of methane below the escape level, in the region from 400–900 km where transport of molecules and chemistry is very poorly known? If methane escape is more important than previously thought, what does this imply about the escape rate of the primary atmospheric gas nitrogen, which based on Voyager estimates is presently about 10% of the total in the atmosphere over the age of the solar system? Might the loss be larger?

5.1 Atmosphere and Surface

In the middle and lower atmosphere of Titan, winds carry solar energy transformed into heat from equator to pole. Cassini has measured the thermal structure of the lower atmosphere in various locations, including the poles, but energy is carried as well in the middle part of the atmosphere above 400 km where almost no information has been obtained. What is the circulation in this region? Even below, the dynamics of the so-called Hadley circulation from equator to pole is highly uncertain. What is the nature of this annual weather system, and is it confined largely to polar methane cloud formation or do convective clouds form at mid-latitudes as hinted by Earth-based observations? What is the detailed morphology of springtime/summer cloud features at the poles? What role do surface methane reservoirs play in latent heat and methane vapor supply and transport? Coverage by *in situ* elements that can probe the clouds directly and synoptic coverage by an orbiter capable of remote sensing at all levels will be required to quantify the nature of Titan’s meteorology.

Titan’s surface is perhaps its most enigmatic and fascinating feature. In only one location—where the Huygens probe drifted at low altitude and then landed—are there high resolution images of the surface. And yet in that small region are seen the effects of liquids carving the landscape, dunes in the distance, hills that speak of planetary tectonics, and a teaser of liquid methane that flowed from the ground into the probe as it sat on a plain dotted with rounded (ice?) cobbles. The remainder of the surface is seen at best at 300–500 m resolution, and here only of order 10–20% of what evidently is a varied and complex world—most of Titan is seen at 1 km and worse. At resolution of hundreds of meters, dunes are positively identified, areas of likely lakes and seas, and broad fluvial valleys, but a raft of surface features ranging from enigmatic

circles hundreds of meters across to mountains to possible lava flows are seen but not understood. The rule of thumb that has served well in 40 years of planetary exploration is that roughly a factor of 10–20 improvement in resolution from one mission to the next is an optimal compromise between getting surface detail and having manageable data volumes to enable a realistic mission.

With the images at hand one can ask a long list of questions: Do the broad fluvial valleys branch into fine dendritic features like those seen at the Huygens landing site? What geologic process—impact, volcanic or otherwise—forms the circular features seen in many radar images? What is the nature of the topographic features that interrupt the dunes? Are the features that look like lava flows in fact cryovolcanic flows? What do the shorelines of the lakes look like—are there sediments on the shorelines, or precipitates of some variety? Are the mountains incised with small-scale channels? And so forth.

Equally ambiguous is the determination of the chemical composition of the surface and of the lakes. Hydrocarbon and nitrile spectral features are seen from Cassini but the spatial resolution is coarse and the compounds responsible are not identified. At the Huygens landing site higher resolution spectra extended only to 1.5 μm, whereas spectra out beyond 5 μm are required to separate various hydrocarbons and organic molecules. Is the chemical composition of the surface correlated with geology in some way? Has acetylene reacted and transformed into other compounds, releasing stored energetic particle and UV energy derived from the high atmosphere? What is the bulk composition of the northern hemisphere lakes? Is methane present in the south's Ontario Lacus in addition to the already identified ethane? Is there evidence for the formation of organics, particularly oxygen-bearing organics, in discrete places on Titan's surface? Is there evidence for interaction between organics and liquid water formed during impacts or cryovolcanism? Are sources of energy for continued evolution of organics available on Titan's surface, such as current cryovolcanism?

Saturn's moon Enceladus provides a second site for testing how far organic chemistry proceeds in the presence of liquid water, assuming that the observed plumes have liquid water at their source. Is there liquid water in Enceladus? Do high molecular weight polymers appear in the plumes? Are oxygen-bearing organics present in the plumes?

Together with images and compositional information, topography is essential for understanding the nature of features on a planetary surface. Cassini was very limited in the topographic information it could derive by various means, and over the vast majority of the planet little or nothing is known about the topography. Why the rivers flow in the direction they do on Xanadu is not understood because the topography is too crude to determine slope directions. The topographic shape of Ganesha Macula, based on Cassini data, does not seem consistent with its interpretation as a cryovolcano, but the altimetric data are crude. Is it a topographic high? What is the topography along the lake shorelines? Are the various lakes in the northern hemisphere at different heights or at a constant level suggestive of the equivalent of a methane aquifer?

The overall sources and sinks of the methane remain poorly understood after Cassini-Huygens, which has eliminated one possible reservoir—a global surface ocean—and hinted at the possibility that methane is stored in a porous ice crust. Some insight into the possibility of a methane (and ethane aquifer) will come from watching the northern hemisphere lakes as the seasons' progress: whether they wax and wane in a manner consistent with isolated basins or are stably supported by a larger underground reservoir. This is an indirect approach, however, and more direct approaches are required to answer whether the crust can or does contain large amounts of methane and/or its product ethane.

5.2 Titan's Interior

Titan's interior also remains poorly constrained at the moment. Determination of the interior structure by the usual technique involving tracking of the spacecraft radio signal has been hampered by the effects of drag on the spacecraft, although some success has been made in determining that Titan's moment of inertia is consistent with some degree of differentiation into a rocky core and an icy mantle. More sensitive radio science measurements, with a means of removing the effects of atmospheric drag, will be required to make more progress. An indication of a

slightly conducting liquid layer (consistent with water and some ammonia) many tens of kilometers below the surface is seen in the dependence of the electric field with altitude measured by Huygens. An intrinsic magnetic field—one generated by a dynamo deep in the interior—appears to be absent, but detection is hampered both Cassini's large flyby distances, and the presence of a shielding ionosphere. It is even more difficult, for the same reasons, to detect a magnetic field induced by the presence of Saturn's. A slightly salty or ammonia-doped water ocean should generate a weak induced magnetic field, and it is important to test for it on future missions.

5.3 Titan's Origin and Evolution

Having proceeded downward from the upper atmosphere to the deep interior Titan must now be considered in time. Cassini will provide information on seasonal variations in the atmosphere for almost 2/3 of a Saturn year if it survives to 2017, which is possible. This will allow a number of questions about the southern polar region to be addressed. Why did Cassini not see many lakes in the southern hemisphere? Do basins in the south fill with liquid in the winter? Does the onset of summer trigger the convective storms seen by Cassini later in the summer? What other seasonal processes are asymmetric between the north and south. On longer timescales the atmosphere may become moist in methane if the equivalent of a terrestrial aquifer exists beneath the high latitude lakes. Are there such aquifers? Are there meteorological processes indicative of a gradual humidification of the atmosphere with time?

Over geologic time Titan has evolved, cooling and thickening its crust. Is there evidence for crustal thickening over time? What is the present-day crustal thickness? Has it thickened recently, or has it been thick throughout the history of Titan? Is there evidence for present-day or recent volcanism, or active geysering of methane, on the surface? Are there reservoirs of ethane or methane that might be detected through crustal profiling or higher resolution imagery or spectroscopy than has been possible to date?

Finally, how did Titan form? What is the origin of its methane? Was it derived from carbon dioxide or from methane—that is, are there patches of carbon dioxide associated with evident cryovolcanic constructs on the surface? The low abundance of argon from Cassini suggests that nitrogen originated as ammonia, but ammonia has yet to be detected on the surface. Why is krypton absent as well? Are there clues in the noble gas abundances, isotopic ratios of major carbon and nitrogen-bearing species, to whether the composition of the circum-Saturnian disk during the ringed planet's formation was distinct from that in the solar nebula?

6. Components of a Future Mission to Titan

Exploration of this complex world-- with its diverse terrains, seasonal and possibly secular changes –will require long-term orbiting and *in situ* exploration, at a season different than Cassini-Huygens: sampling of the organic phases (most easily accomplished by a lander in the polar seas), high resolution profiling of the crust and high resolution imaging of large areas of the surface (best accomplished by a hot air balloon) and a comprehensive set of mapping and profiling instruments for the atmosphere, surface and ionosphere situated on a Titan orbiter. A summary of such a mission is provided in the TSSM final report http://opfm.jpl.nasa.gov/library/.

7. References

A complete reference list covering the science of Titan described here will be found in the TSSM Final report at http://opfm.jpl.nasa.gov/library/. Other recent review references are:

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